UCRL-84151
PREPRINT

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This paper was prepared for submittal to the
International Nuclear Reactor Safety Heat
Transfer Seminar, Dubrovnik, Yugoslavia
September 1 - 5, 1980

April 1, 1980

THE PHYSICAL MODEL OF LEAN SUPPRESSION PRESSURE OSCILLATION PHENOMENA - STEAM CONDENSATION IN THE LIGHT WATER REACTOR PRESSURE SUPPRESSION SYSTEM (PSS)*

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ABSTRACT

Using the results of large scale multivent tests conducted by GKSS, we have developed a physical model of chugging. The unique combination of accurate digital data and cinematic data has allowed us to obtain detailed, quantified correlation between the dynamic physical variables and the associated two-phase thermo-hydraulic phenomena occurring during lean suppression (chugging) phases of the loss-of-coolant accident in a boiling water reactor pressure suppression system.

* This work was supported by the United States Nuclear Regulatory Commission under a Memorandum of Understanding with the United States Department of Energy.

1. INTRODUCTION

Previous boiling water reactor (BWR) pressure suppression experiments in Europe and in the United States have provided significant advances in the understanding of pressure suppression system (PSS) function and efficiency in the case of a hypothetical loss-of-coolant accident (LOCA). Although the principle is simple, the resultant transient phenomena exhibit complex components which give rise to significant impulsive loading in the wetwell difficult to quantify but important to safe design.

Past studies have identified numerous pressure suppression phenomena which accompany the quasi-steady state pressure and temperature rise in the PSS wetwell during a hypothetical LOCA. The transition from initiation of break flow to completion of blow-down is accomplished in three consecutive stages as shown in the plot of pool bottom pressure in Fig. 1:

- clearing of the initial water leg in the vent pipes by steam-driven wetwell air, resulting in a single strong impulsive loading cycle on the pool boundary coupled with a strong pool swell as the non-condensible drywell air creates a large subpool bubble at each vent exit followed by an air-rich flow period.
- an extended period of quasi-steady state steam condensation termed condensation oscillation (CO), which is periodic and accompanied by regular pressure variations on the pool boundaries.
- lean suppression or chugging, which occurs under conditions of low air content and depleted steam flow and which gives rise to strong, impulsive pressure transients of variable magnitude. Because of the strong and cyclic nature of this chugging stage, its quantification is of considerable importance to safe containment design.

In order to resolve unanswered questions, clarify the phenomenology of pressure suppression processes, and contribute to both development and verification of computer models, the GKSS, in coordination with interested institutions of West Germany and the United States, was commissioned in 1977 to develop a test program for such basic research on a multivent BWR-related pressure suppression system.[1] The Lawrence Livermore Laboratory (LLL) was designated in 1979 as the principal U.S. NRC liaison for this test program, with particular emphasis on developing confirmatory data for use in the licensing of U.S. Mark II nuclear power plants. The multivent test facility[2], placed in operation in February 1979, provides a three-pipe full-scale vent system (see Fig. 2) modelling main features of both the West German KWU and United States G.E. MK II BWR pressure suppression system. The time-correlated measurements system consists of 128 - 25 Hz and 60 - 1.7 kHz test data transducers, three 50 Hz television cameras which view both the water surface regions and vent pipe outlets in the wetwell, and a high speed (1000 fps) 16 mm camera which observes a single vent pipe outlet. The combination of cinematic data with vent pipe and wetwell pool pressure and temperature data have combined to allow the identification and description of the physical model of the chugging processes.

2. MODEL DEVELOPMENT

The work reported here is based on the study of several multivent tests[3] and quantified by the results of a particular test (M2), conducted at defined standard initial conditions. As with the other tests, it was intended to study the entire LOCA transient and does not address possible secondary influences of initial condition variations in such parameters as vent submergence or pool temperature. This work is based on results from a currently active test program and, therefore, is of a preliminary nature and is expected to be expanded. Using a typical chugging event, we will demonstrate how numerical data can be intercompared and then correlated with visual data to obtain a clear understanding of the chugging process.

2.1 Description of a Typical Chugging Event

A chugging event is identified with an apparent starvation of steam flow and is accompanied by a strong high frequency pressure oscillation observable throughout the wetwell, drywell, and vent exits. As a typical train of pressure pulses shows (Fig. 3), the individual dynamic events occur in a periodic manner, in this case at an approximate frequency of 0.3 Hz. Closer examination of a single pulse (Fig. 4) shows that, in general, an individual chug event is characterized by an initial pressure decrease leading into a series of relatively low frequency oscillations. These oscillations end with a sharp rarefaction followed by a series of higher frequency and amplitude oscillations which gradually decay. The rarefaction, characteristic of all chug events, is not always preceeded by a low frequency oscillation.

The GKSS test results to date consistently indicate a strong coupling among dynamic events throughout the entire experimental facility. Thus, if the event time of the chug in Fig. 4 is compared to the train in Fig. 3, a corresponding similar dynamic event can be located at the same time, even though the pool bottom transducers are respectively located directly beneath a vent pipe and in one corner of the wetwell. This coupling is further illustrated by the close correspondence of the pressure behavior in the drywell (Fig. 5) with that observed in the wetwell.

This coupling of dynamic events is important for a number of reasons:

- it implies that the behavior of the three vent pipes is synchronous. Therefore, the dynamic character of transducer measurements and visual observations made at any vent pipe may be considered to be qualitatively representative of the behavior at all three vent pipes.

- it implies that the chugging <u>process</u> is not significantly dependent on the facility. The previously discussed correlation between pool bottom transducers WW-PA52 and WW-PA42 aids in illustrating this point. Despite the fact that one transducer is located in a corner of the wetwell (where structural influences on the pressure measurements could be expected to be greatest) and the other directly beneath a vent pipe, both show essentially the same dynamic behavior.

- it implies that a pool bottom transducer directly beneath a vent pipe (e.g., WW-PA42) may be used with confidence to correlate numerical data with visual observations at the vent exit.

The fact of event correlation is particularly important with regard to the work reported here. Transducer WW-PA42 is located directly beneath vent pipe "A", where high speed 16mm movies were made of steam flow at the vent exit. A typical chug observed at this location will provide the discussion case for comparing visual and numerical test data.

2.2 Data Selected for Correlation

As shown schematically in Fig. 2, the data selected to illustrate the correlation of dynamic events in the GKSS tests covers measurements made from the drywell to the wetwell, i.e., from "source" to "sink". In this manner, coupled input and output conditions can be used to verify analytical models.

The focus here is on pressure and temperature measurements. Pressures represent the actual loads seen by the system, as well as the corresponding forcing functions, and can be correlated with other dynamic events (e.g., temperature) to establish accurate event times and possible triggering effects. The temperature measurements, aside from their obvious importance for defining thermodynamic conditions, are used to determine the location of the chug condensation front along the axis of a vent pipe. Such use of temperature measurements to gauge level swell, which was discussed earlier[4], utilizes the large variation in temperature observed as the temperature probe is alternately exposed to steam or water flow.

These numerical measurements can be coupled to visual data. At vent pipe "A", high speed 16mm movies (using a nominal framing rate of 1000 frames/s) are available for the time period 137.4 to 149.3 seconds, which covers four chugging events. Selected frames of this film were studied to identify such features as steam intrusion into the pool and distribution about the vent exit.

2.3 Data Correlation - Multiple Pulses

Correlation of data at selected locations in the GKSS facility will begin by addressing the train of three chug events that occur between 140.0 and 150.0 seconds into the M2 test.

As previously discussed, it is possible to track the propagation of the condensation front into and out of the vent exit by examining data from the nine temperature transducers located from 300 mm above the vent exit (channel KA-TMF0) to 300 mm below the vent exit (channel KA-TMF8). Note in Figs. 6 and 7, which show the temperature variations during two of these chugging events, that all of the transducers are initially at a uniform temperature of approximately 55°C, indicating that the vents are temporarily in a state of reflood. As the steam flow becomes reinitiated in the vent, each transducer is successively exposed to steam flow, as evidenced by a marked increase in temperature. When the condensation front reverses and vent pipe reflood once again occurs, the temperature returns to its initial level; we note, however, that the temperature transducer deepest in the pool below the vent pipe (KA-TMF8) does not reach the steam temperature (~125°C) indicating that the transducer was exposed to steam flow for a period of time less than its response time.

Using the appropriate inflection points in the temperature traces to define the steam-water interface, i.e., time at which the flow condition changed at a given transducer, plots of the interface position as a function of time are developed as shown in Figs. 8 and 9. Considering the condensation front propagation determined in this manner with the noted observations made from the high speed film, a strong correlation is seen to exist between numerical and visual observations when the times of the start of steam flow from vent A and of the maximum in-pool steam intrusion are compared with the transducer data. It is interesting to note from Figs. 7a and 9 that a strong single oscillation in water level occurs in the vent pipe just prior to the start of steam flow from the vent exit. This nearly instantaneous reversal of fluid flow before vent clearing finally occurs creates an apparently strong "piston" effect in the vent that is not observed elsewhere in the system. The start of steam flow and the times of maximum steam intrusion corresponding to the second and third chug events respectively as shown in Fig. 10. For both pulses considered, the maximum in-pool steam intrusion corresponds to the second (b) strong negative pressure peak, while the start of steam flow from the vent occurs slightly after the initial negative pressure inflection (a) in each case. The time of the maximum rarefaction for each chug pulse has also been included in Fig. 10. It is of interest to note that this rarefaction (d), and the subsequent sharp positive pressure spike and decay, occurs well after the time of maximum steam intrusion into the pool.

The maximum rarefaction, which acts as a precursor of the sharp pressure spike and subsequent pulse decay observed at the vent exit, corresponds to the minimum in-vent pressure (Fig. 11). After the chug occurs, pressure in the vent increases until it once again is sufficient to clear the vent exit, and reinitiate the lean suppression process. The dynamic character of the in-vent pressure and temperature is similar, with the maximum temperature gradient coincident with the sharp decrease in pressure observed for all three events.

This coupling is preserved as we continue into the drywell. The measured temperature and pressure (Fig. 11) continue to exhibit similar dynamic behavior as the corresponding conditions in the vent pipe.

The dynamic characteristics of the pool bottom response are also closely coupled to the behavior at the vent exit. As shown in Fig. 12, the start of the steam flow again corresponds with a point just following the first negative pressure inflection for each of the two pulses considered here. The maximum rarefaction for each pulse, which at the vent exit preceeded the positive pressure spike, exhibits the same behavior for the pool bottom response.

The pressure response of the wetwell air space (ullage) also appears closely coupled to the carrier response at the pool bottom.

2.4 Data Correlation - Single Pulse

Modelling of the lean suppression event in the GKSS facility will next be discussed for a single representative chug event. The chug shown earlier in Fig. 4 includes the timing of steam flow events. It was selected because it is typical of a common type of chug observed during the tests, and because it evidences two distinct and important types of dynamic behavior.

Of principal interest from the structural point of view is the rarefaction at 148.94 seconds, followed by the sharp pressure spike and subsequent constant frequency ringdown. The frequency of the ringdown is about 35 Hz, equal to that characteristic of the GKSS wetwell structure,[2] indicating that these oscillations are the result of excitations of the natural frequency of the experimental facility. Examination of the high speed film data shows that the retreating condensation front in the pool temporarily terminates with the formation of the steam ring (or annulus) inside the rim of the vent pipe exit. This ring remains stable while the water re-enters the vent pipe, but suddenly collapses at the indicated time of maximum rarefaction. It would appear that it is the collapse of this steam ring that initiates the subsequent high frequency pressure response observed in Fig. 4 so characteristic of the lean suppression process. High speed film data for other chug events indicates that the formation and collapse of this steam ring is a consistent precursor to the high frequency chug pressure response.

The second feature of interest in Fig. 4 is the lower frequency pressure oscillations that preceed the occurrence of the rarefaction. These oscillations have a frequency of about 11.1 Hz, very near to the acoustic frequency (11.01 Hz with an estimated local sound speed of 487 m/sec) of the steam-filled vent pipe. Unlike the high frequency, structure-related oscillations following the maximum rarefaction, these acoustic waves are not generally observed for all chug events. This "mixture" of chug types has been observed in all of the LOCA simulation tests at GKSS. The initiating event for these acoustic waves is not immediately apparent, but examination of the temperature traces from transducers along the vent axis (Fig. 2) offers a possible clue as to their origin. The temperature traces shown in Fig. 7 for transducers KA-TMF0 through KA-TMF7 all consistently evidence a negative inflection at about 148.7 seconds followed by a positive inflection at about 148.71 seconds, indicating a rapid chilling of these transducers. These results indicate a nearly simultaneous and short lived flooding cycle at all measurement points. During this period both high speed film and TV film indicates continuous steam flow but this of course is viewed by reflected light and from the side of the condensation volume. Recalling our earlier observation that F8 (at 300mm below the vent exit) did not reach steam temperature (see Figs. 8b and 9b),
even though the apparent maximum penetration of the condensation front (CF) extends well beyond that position, we conjecture that the condensation volume may be partially hollow thereby admitting pool water into the central region and above the apparent CF. Carrying this thought one step further, such a configuration of the CF would naturally tend to develop the observed steam ring which remains after "cessation" of steam flow from the vent.

As with the multiple-event data previously discussed, definite coupling can be observed between the pool bottom response and that measured elsewhere in the facility. Significant feedback is evident; examination of pressure deviations at the vent exit (Fig. 13), for example, shows two strong positive pressure peaks which correspond to the structurally induced peaks measured at the pool bottom at 148.95 and 148.98 seconds.

The acoustic oscillations between 148.7 and 148.9 seconds are also evidenced, but do not appear as distinct as at the pool bottom. This is most likely an artifact of channel KA-PG16 being a piezoelectric transducer, which only measures deviation from what is a continually varying reference pressure.

The acoustic response is more clearly evident in-vent where it does not begin until the vent is cleared, i.e., when the vent is completely filled with steam and a true acoustic system has been established.

Definite acoustic components are not obvious in the drywell pressure response, probably a result of dissipation at the junction of the vent pipe and the "infinite" drywell volume.

3. DISCUSSION OF RESULTS

In the GKSS-PSS tests to date, we have observed a consistent and close coupling of events throughout the drywell, wetwell, and vent pipes as well as a strong correlation between physical and high-speed visual data obtained from the tests. Using these results we provide a model of the lean suppression process:

- the lean suppression (chugging) events evidence a strong positive pressure peak followed by a high-frequency ringdown characteristic of the natural frequency of the submerged wetwell structure.

- this ringdown is preceeded by a strong rarefaction that is correlated to the formation and rapid collapse of the steam ring which forms at the vent exit at the end of steam flow.

- in some cases, a period of lower frequency but strong amplitude oscillations preceeds the chug rarefaction. The frequencies of these pre-chug oscillations correspond to the acoustic frequency of the particular vent pipe.

- evidence collected from temperature transducers and high speed film suggests the steam plume, which penetrates into the pool prior to chug initiation, is partially hollow, thereby allowing a momentary chilling transient to trigger or initiate the acoustic wave. The collapse of such a hollow-core plume could conceivably give rise to the steam ring formed inside the vent exit.

This initial investigation of the GKSS-PSS multivent tests has documented the consistent correlation between physical and visual data observed and provides a new and useful basis for the further development of advanced computer models which address the lean suppression process in a LOCA. In addition, during development of the physical model, additional two phase phenomena were identified which will require further work, now in progress, to be clearly understood and quantified. In this regard, the formation of the steam annulus at the vent exit preceeded by the possible formation of a partial hollow in the steam plume which penetrates the pool during steam flow are of particular interest. The effects of vent acoustics are also candidate for further attention.

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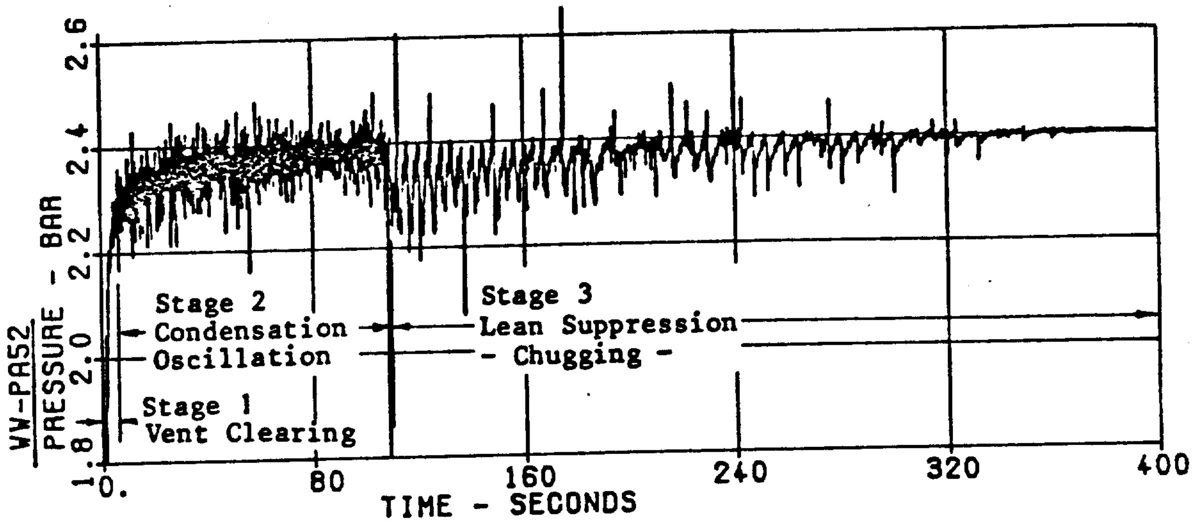

Fig. 1 Stages of Response During the LOCA Simulation

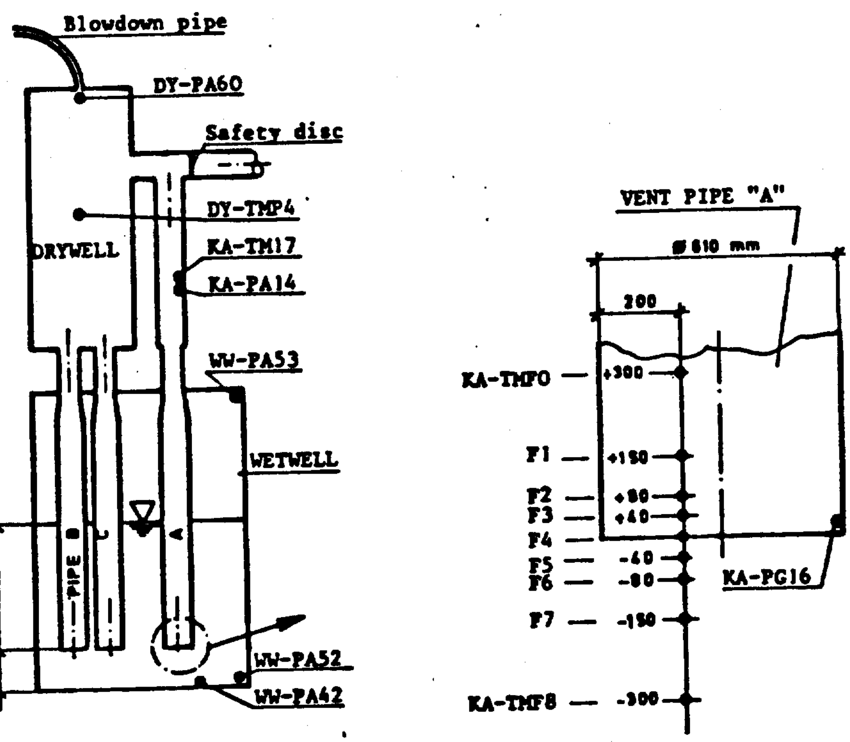

Fig. 2 Schematic of GKSS Multivent Test Facility and Selected Transducer Locations

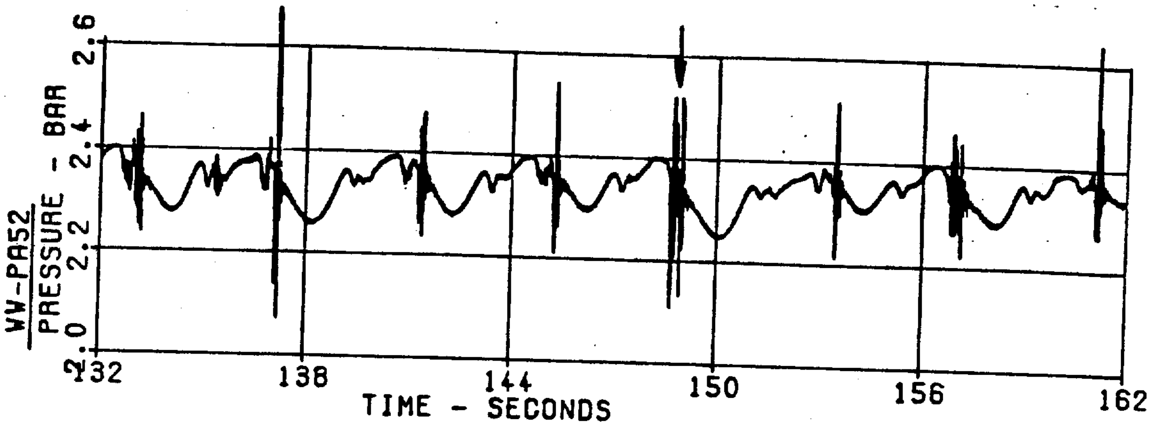

Fig. 3 Typical Chug-Mode Pressure Response in Wetwell

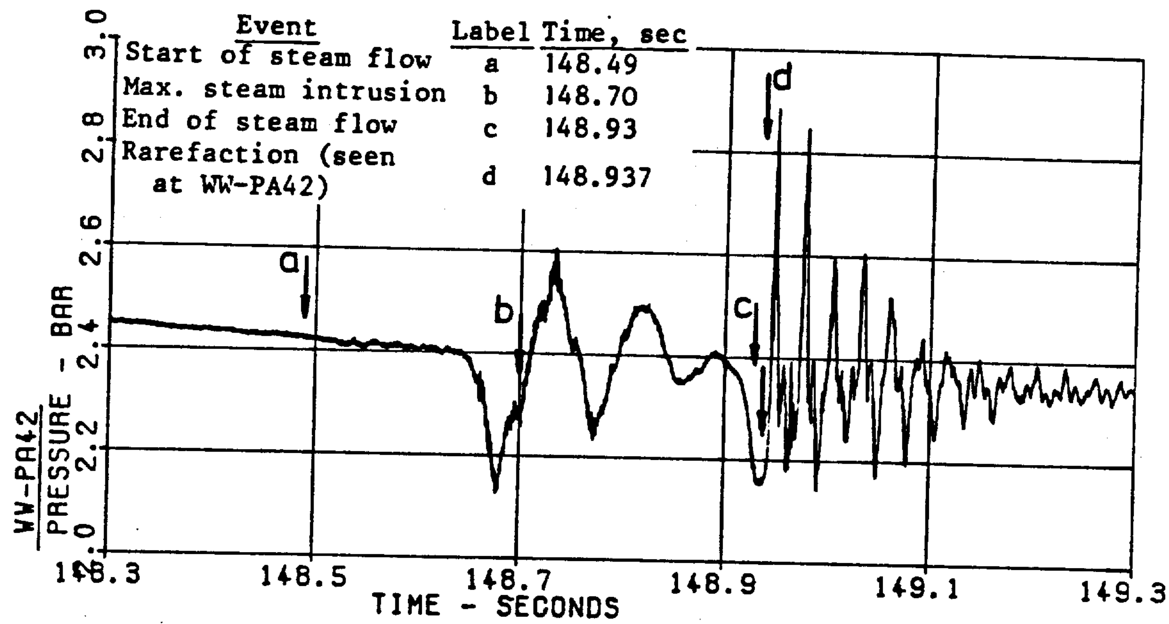

Fig. 4 Detail of Lean Suppression Condensation Event Correlation of Pool Boundary Response with Observed Steam Flow

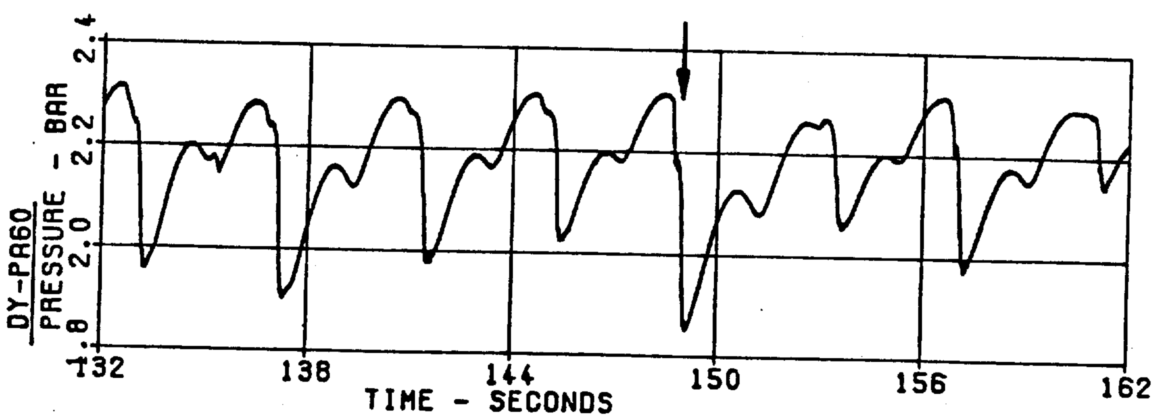

Fig. 5 Typical Pressure History in Drywell During Chugging

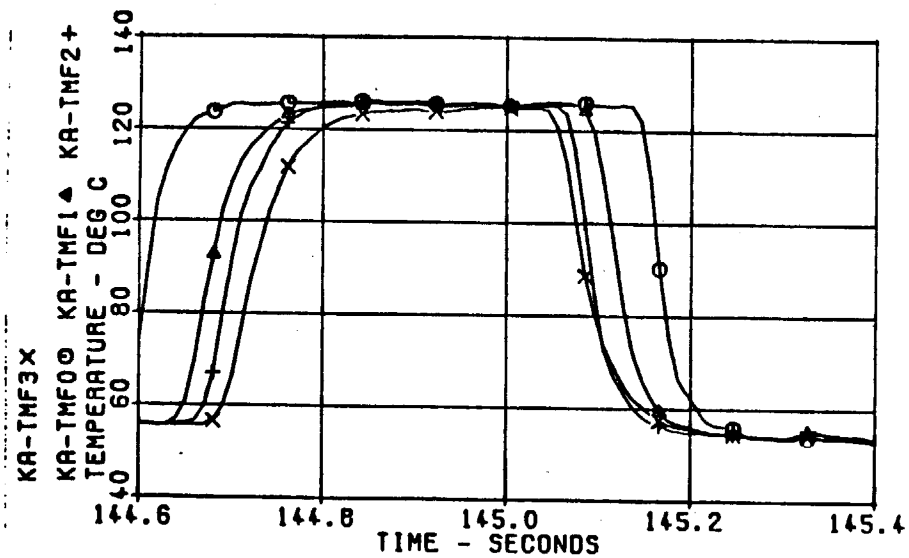

Fig. 6a Temperature History near Vent Exit, In-Vent

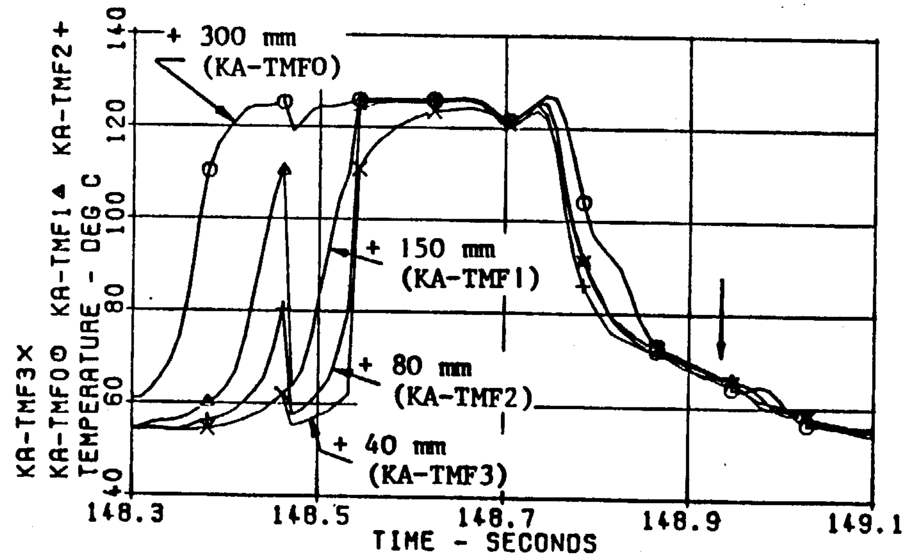

Fig. 7a Temperature History near Vent Exit, In-Vent

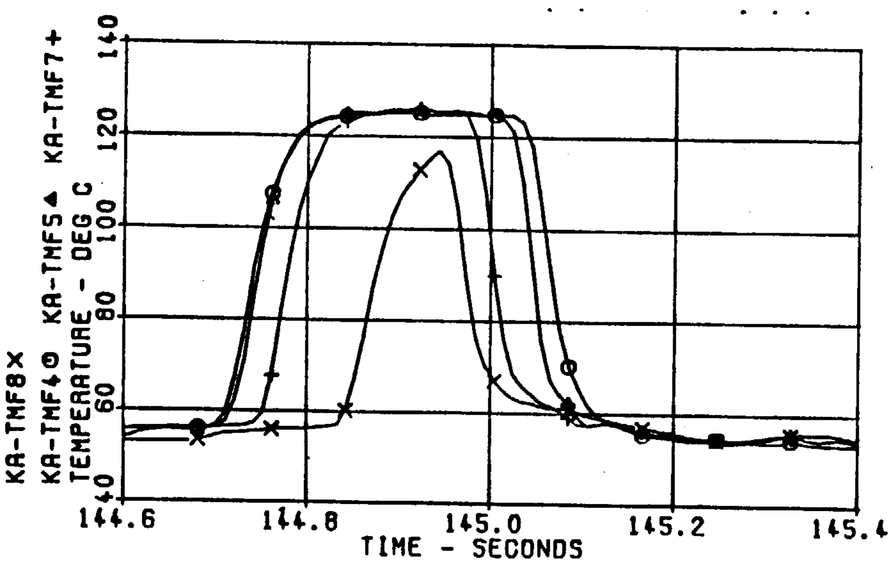

Fig. 6b Temperature History near Vent Exit, below Vent

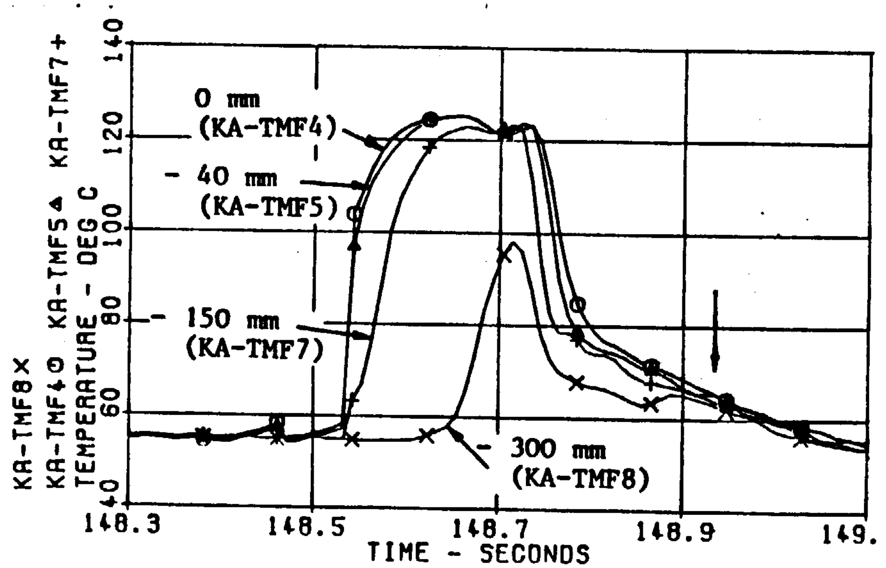

Fig. 7b Temperature History near Vent Exit, below Vent

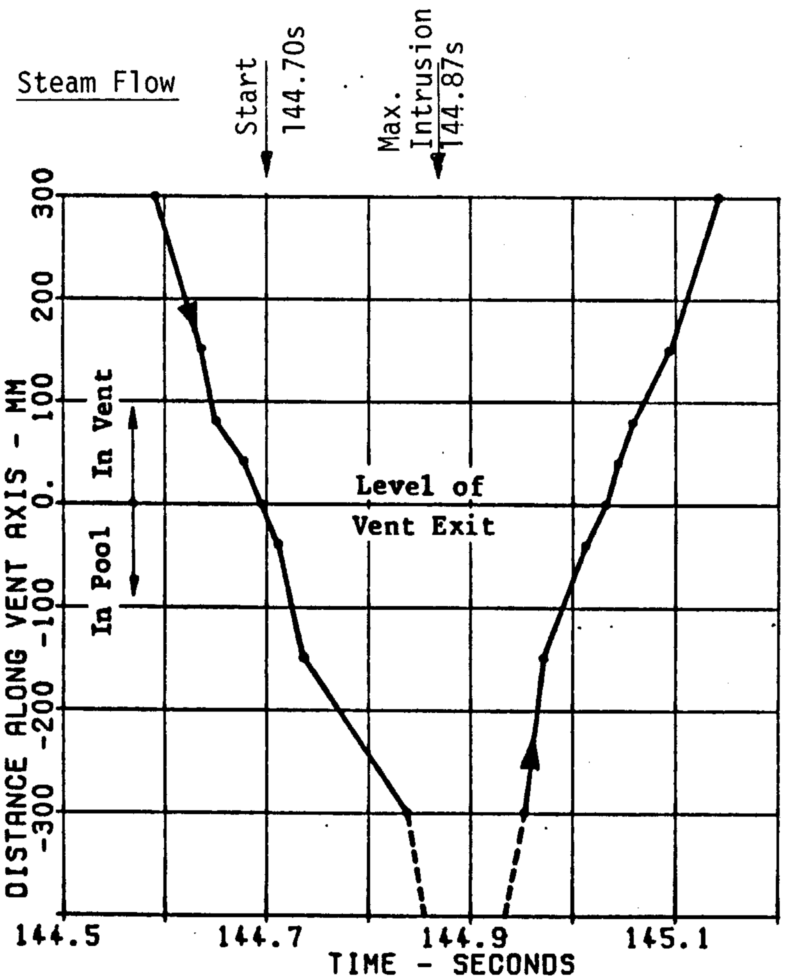

Fig. 8 **Correlation of Steam-Water Interface Motion with Steam Flow - No Acoustic Response**

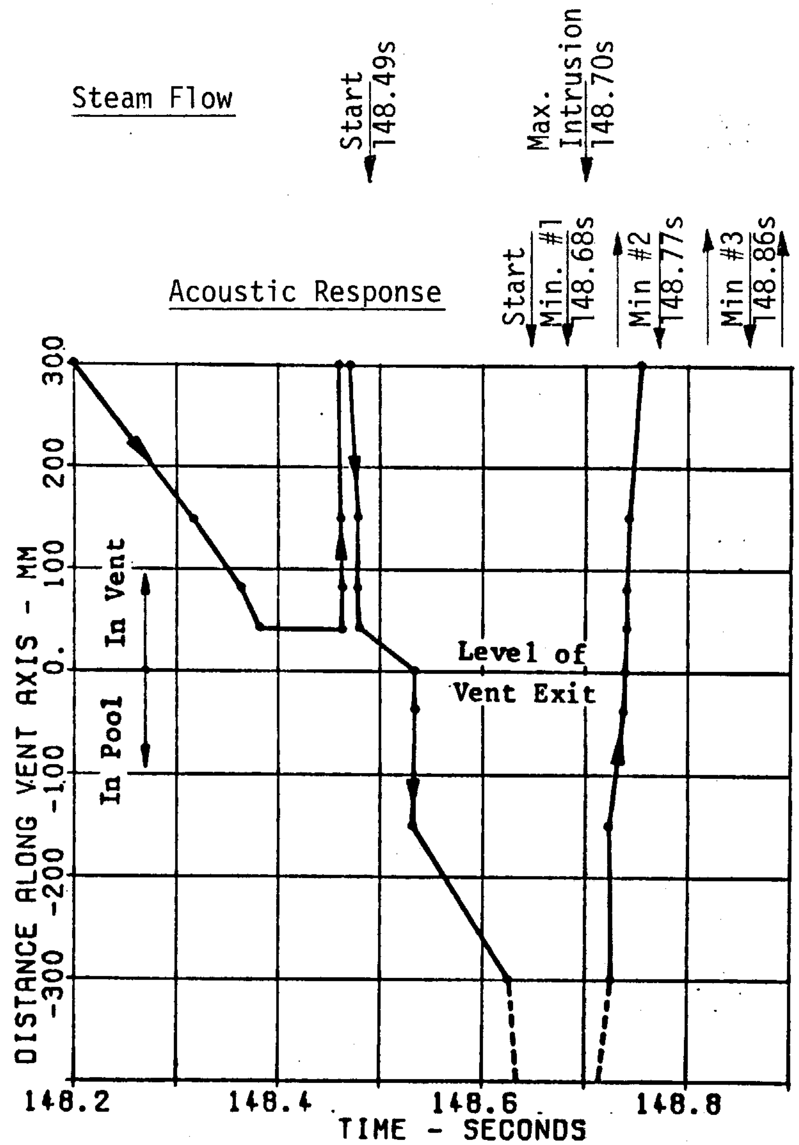

Fig. 9 **Correlation of Steam-Water Interface Motion with Steam Flow - With Acoustic Response**

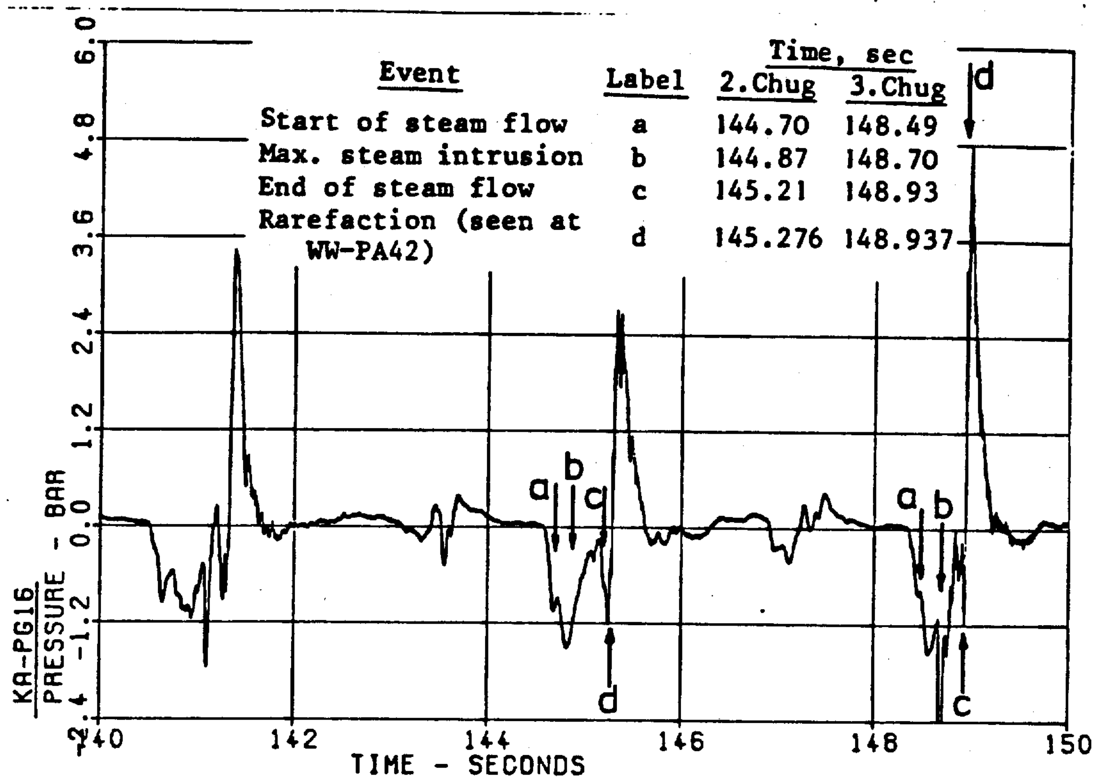

Fig. 10 Vent Exit Pressure History with Steam Flow Correlation

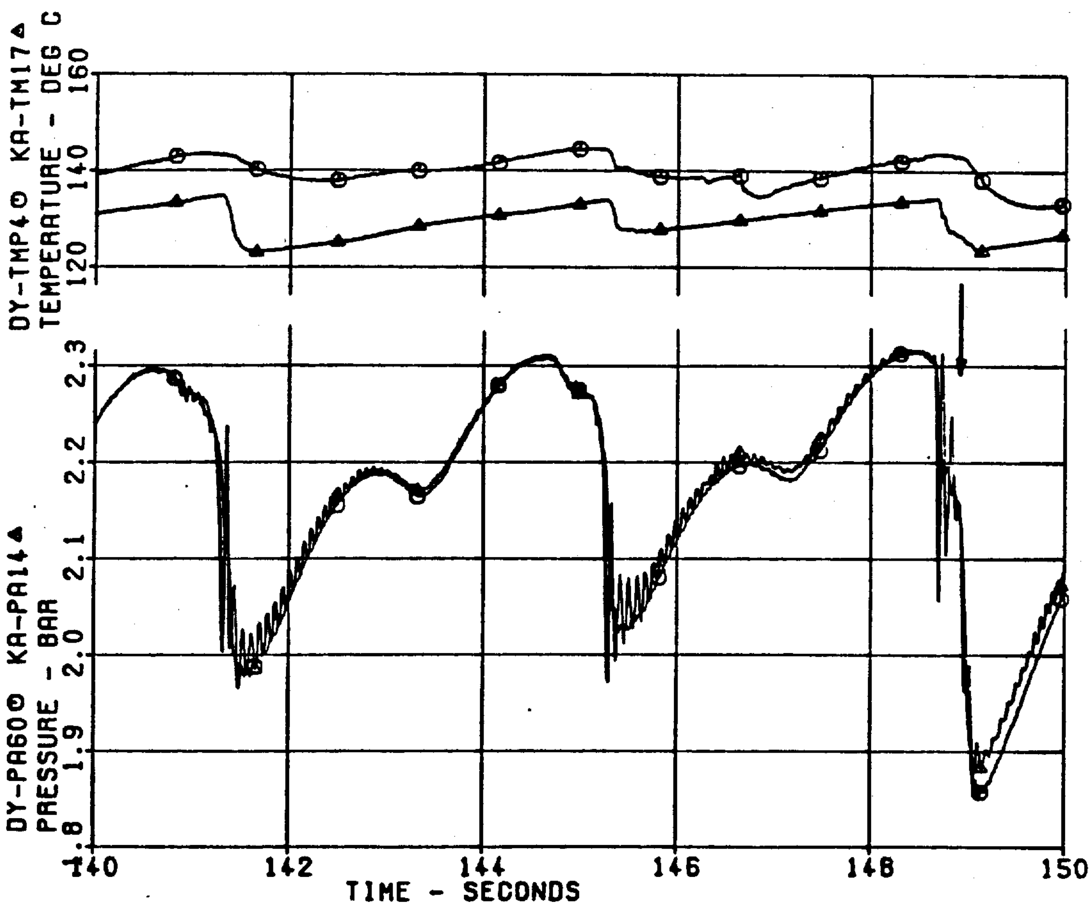

Fig. 11 Drywell and In-Vent Temperature and Pressure History

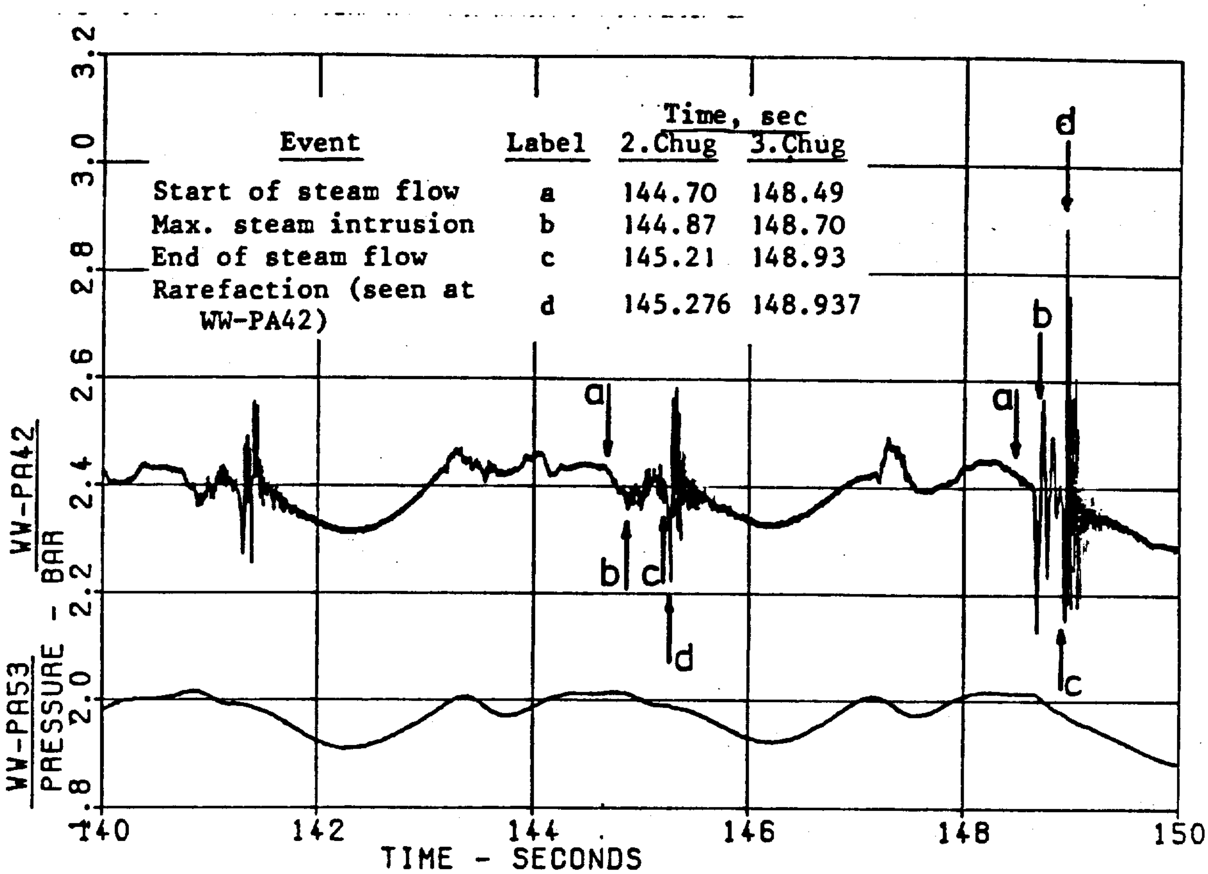

Fig. 12 Wetwell Floor and Ullage Pressure History

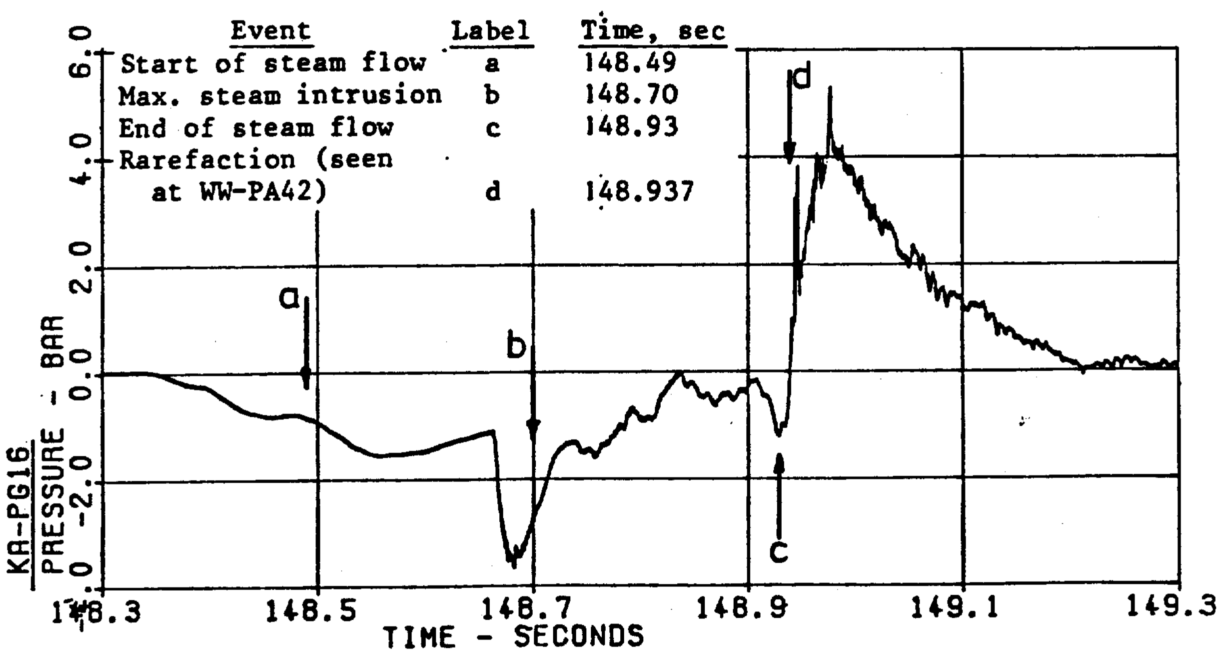

Fig. 13 Vent Exit Pressure History (Detail)